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Vacuum breakdown of sub-micrometer gap with pointed electrode

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Vacuum breakdown of very small gap in the range of 30nm to 2f m, between a pointed cathode of thin tungsten wire and a plane anode of stainless steel, was experimentally investigated. The experimental setup, which consists of both electrodes and precise positioning mechanisms actuated by piezoelectric devices, was installed in scanning electron microscope (SEM). Breakdown voltage decreases with decrease of gap spacing and/or radius of curvature at the tip of cathode. Theoretical consideration shows that the evaporation from the anode surface heated by field emission current is dominant factor of triggering vacuum breakdown.

1. Introduction

Recently, various materials processing techniques have been actively developed in order to produce micro-machines and/or micro-robots used for medical instruments, sensors, inspection/repair of piping in nuclear power plants or chemical process plants, and so on. The silicon based micro-parts have been almost produced by means of a photolithography which is frequently used in fabrication of semiconductor ICs. On the other hand, the metal based parts have been shaped by LIGA process and/or focused ion beam (FIB) process. These precise processes are based on the material removing technique; photo-chemical reaction, laser ablation and ion beam sputtering.

However, a micro-joining technique, which includes welding and solid state bonding, will be surely required to produce or assemble more complex structure of the micro-parts. In order to carry out micro-welding successfully, heat power must be precisely controlled and concentrated on the microscopic area. Accordingly, in addition to laser and/or electron beam, of which the beam size can be focused or varied, micro-discharge is possible to be adopted as the heat source. Because the energy generated in the electric discharge partly flows into both of the cathode spot and the anode spot, which are very small regions formed on the surface of each electrode. The energy released from these local areas is spent on heating, melting and evaporation of the electrode material. The goal of the present research and development is to achieve micro-sized welding by use of discharge energy, which is 1/1000 scale-down compared with conventional welding as now practiced widely.

In this paper, in order to establish the discharge condition with a pointed electrode as the first step of micro-welding, vacuum breakdown of very short gap, between a pointed tungsten cathode and a plane stainless steel anode, was experimentally investigated. And the shape and the size of melting spots on the anode surface were also examined.

2. Experimental apparatus and procedure

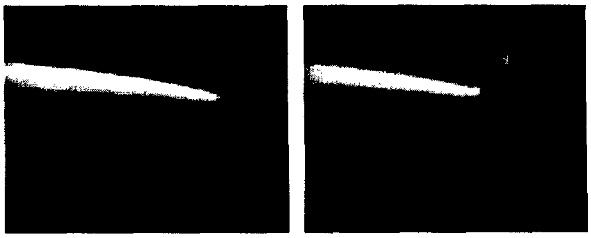
The experimental setup mainly consists of the pointed tungsten cathode of 0.1 mm in diameter, the stainless steel plate anode, the electric circuit and the actuators for adjusting the gap length. The cathode tungsten is mounted on the piezoelectric device, which is used as a fine adjusting actuator that controls the gap length with the accuracy in the order of nanometer. The piezoelectric device is set on a positioning stage driven by pulse-motor, which is a coarse adjusting device. This experimental setup is installed in a SEM in order to carry out the *in-situ* observation of both electrodes before and after micro-discharge.

The shape of the electrode tip affects on the breakdown of the gap or the current distribution of the discharge. The use of the tip having a small radius of curvature increases the local electric field of the gap near the tip. And it may limit the area of electric current flow into the specimen surface. Accordingly, the tip of the tungsten wire is sharpened by electrochemically etching in the 10% NaOH solution. For the plane anode, the surface of stainless steel is buff-polished.

The following procedure was employed in the experiment. With the aids of SEM observation, the tungsten electrode was gradually brought nearer and then softly contacted with the anode surface by driving the actuators. This position was adopted as the origin of the distance for discharge gap spacing. And the gap length was adjusted and determined from voltage applied to the piezoelectric device.

3. Experimental results and discussions

Fig. 1 shows SEM images of both electrodes before and after electrical breakdown. As seen in Fig.1 (b), the melted area is formed at the specimen surface just under the tungsten electrode. This melted spot size seems to depend on the no-load voltage, the gap length and the shape of electrode tip.



(a) Before breakdown (b) After breakdown

Fig. 1 In-situ observation of both electrodes before and after the electrical breakdown.

Fig. 2 shows the relationship between the gap length and the breakdown voltage. When the curvature radius of the tungsten electrode tip is kept constant, the breakdown voltage decreases with decrease of the gap length, and goes down to about 20 volt at the gap length of 30nm. At the same gap length, the breakdown voltage increases with increase of the curvature radius. From the experimental results, the nominal field strength across the gap for the occurrence of breakdown gives the value in the range between 2 • 10^8 • 1 • 10^9V/m. Therefore, it is deduced that the field emission current from the cathode plays important roles for the initiation of breakdown.

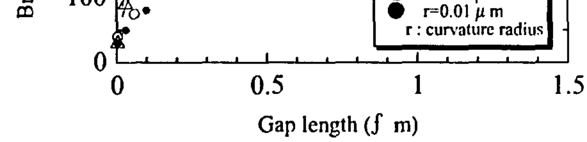


Fig. 2 Change of the breakdown voltage by the gap length between pointed cathode and plane anode in SEM vacuum environment.

Then, the field strength at each point of the electrode surface was calculated on the assumption that the electrode shape is axial symmetric. Next, the field emission current distribution was calculated using Fowler-Nordheim equation. The emitted electron is accelerated by the voltage applied between the cathode and the anode. So, the power density distribution at the anode surface can be calculated as shown in Fig. 3.

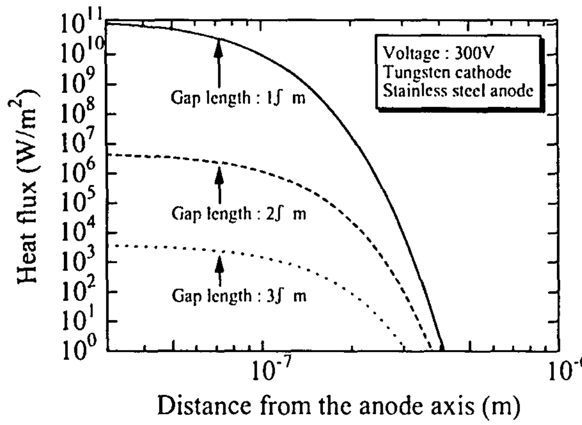


Fig. 3 Heat flux distribution at the anode surface by field emission current as a function of gap length.

As seen, the heat flux or the power density of emission current is concentrated within the radius of 0.1ʃ m and it greatly increases with decrease of the gap length. Accordingly, the very small area of anode surface is rapidly heated up. The temperature distribution at the anode surface can be obtained through the calculation of heat conduction. The solid line and dotted lines in Fig. 1 indicate the calculated results of the relationship between the gap length and the voltage applied, that the temperature of the anode surface reaches boiling point of stainless steel. The calculated voltage is higher than the experimental breakdown voltage, but it seems to be the measure of breakdown. Because the evaporation in vacuum occurs sufficiently at the temperature lower than boiling point. Therefore, the accelerated electrons from the cathode collide with the metal vapor and the avalanche-like accumulation of electrons and ions rapidly occurs in the gap, that is, the breakdown occurs.

4. Conclusions

(1) Vacuum breakdown of sub-micrometer gap between the pointed cathode and the plane anode is governed by the gap length and the curvature radius of cathode tip.
(2) The evaporation from the anode surface heated by the field emission current triggers the electrical breakdown.